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PHYSIOLOGICAL RESPONSES TO MICROCLIMATE COOLING USED BY THE AIR SOLDIER DRESSED AT MOPP 4 IN AN EXTREME DESERT CONDITION: EFFECTS OF SIX CONFIGURATIONS

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14. ABSTRACT

This study supported the Technology Systems and Program Integration Directorate at the U.S. Army Natick Research, Development and Engineering Center as part of its effort to provide PM Air Warrior with the most effective MCCS for its personnel by evaluating the cooling potentials of two prototype MCCS. The two liquid vapor compression cooling units differed in size, weight, and cooling capacity. One system (LO) was 93 cubic inches, and weighed 3.2 kg, with a cooling capacity of 120 W. The other cooling unit (HI) was 201 cubic inches, and weighed 4.6 kg with a cooling capacity of 180 W. The purpose of this study was to support PM-Air Warrior?s efforts to field lightweight portable MCCS for helicopter support crew working in hot environments who may be required to work up to 11 hours. During flight operations, Aircrew may have to wear complete CBRNE protective clothing and equipment, as well as body armor and helmets, while performing their duties. The insulation and low permeability of the garments impedes heat loss and the added weight of armor and equipment increases the metabolic rate. The net result is increased heat strain. This study determined how well two developmental MCCS reduced heat strain under these conditions, despite the additional load carriage (i.e. weight of the MCCS). The study also compared the effectiveness of the modified Army Combat Shirt (ACS) relative to the standard Air Warrior micro-climate cooling garment (MCG). After completing heat acclimation trials, eight male volunteers took part in 6 heat stress tests, with 6 clothing and equipment configurations all worn at MOPP 4. All tests were performed in a simulated extreme desert environment (51.7?C dry bulb (Tdb), 16.6?C dew point (Tdp) (14% rh), 1.3 m∙sec-1 wind speed). Each experimental trial consisted of three repeats of 35 minutes walking on a level treadmill at 3.2 km∙h-1 (2.0 mph) followed by 25 minutes of rest, for a total heat exposure of 180 min. Time weighted mean metabolic rate during the experiments was 269 watts. Each trial was a maximum of 3-hours, or until a given volunteer reached a core temperature of 39.5?C, or voluntarily withdrew. In summary, both cooling systems reduced physiological heat strain measures relative to no cooling. Under the test conditions, neither cooling system provided sufficient cooling to allow for 11 hour flight missions while dressed at the MOPP 4 level. Testing the cooling systems at a more realistic temperature such as the 37.8?C (100?F) that was used in the flight simulator when the original Air Warrior system was developed, might better discriminate between the two systems and provide a clearer picture of how long Air Soldiers could work in the field.

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The investigators have adhered to the policies for protection of human subjects as prescribed in Army Regulation 70-25, and the research was conducted in adherence with the provisions of 32 CFR Part 219.

Human subjects participated in these studies after giving their free and informed voluntary consent. Investigators adhered to AR 70-25 and the USAMRMC Regulation 70-25 on the use of volunteers in research.

Any citations of commercial organizations and trade names in this report do not constitute an official Department of the Army endorsement of approval of the products or services of these organizations.

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LIST OF ABBREVIATIONS

ACS – Modified Army Combat Shirt in no cooling configuration

ACS HI – Modified Army Combat Shirt Used in High Cooling Configuration

ACS LO – Modified Army Combat Shirt Used in Low Cooling Configuration

ACU – Army Combat Uniform

APFU – Army Physical Fitness Uniform

CON – No Cooling Configuration wearing a t-shirt

HR – Heart Rate

IOTV – Improved Outer Tactical Vest

MCCS – Microclimate Cooling System

MCG HI – Air Warrior Microclimate Cooling Garment Used in High Cooling Configuration

MCG LO - Air Warrior Microclimate Cooling Garment Used in Low Cooling Configuration

MOPP 4 – Mission Oriented Protective Posture Level 4

NSRDEC – Natick Soldier, Research, Development, and Engineering Center

RH – Relative Humidity

SR – Sweat Rate

T_c – Body Core Temperature

T_{db} – Ambient Dry Bulb Temperature

T_{dp} – Ambient Dew Point Temperature

T_{sk} – Mean Weighted Skin Temperature

USARIEM – U.S. Army Research Institute of Environmental Medicine

WBGT – Wet Bulb Globe Temperature

EXECUTIVE SUMMARY

This study supported the Technology Systems and Program Integration Directorate at the U.S. Army Natick Research, Development and Engineering Center as part of its effort to provide PM Air Warrior with the most effective microclimate cooling system (MCCS) for its personnel by evaluating the cooling potentials of two prototype MCCS. The two liquid vapor compression cooling units differed in size, weight, and cooling capacity. One system (LO) was 93 cubic inches, and weighed 3.2 kg, with a cooling capacity of 120 W. The other cooling unit (HI) was 201 cubic inches, and weighed 4.6 kg with a cooling capacity of 180 W.

The purpose of this study was to support PM-Air Warrior's efforts to field lightweight portable MCCS for helicopter support crew working in hot environments who may be required to work up to 11 hours. During flight operations, Aircrew may have to wear complete chemical, biological, radiological, nuclear, and explosive (CBRNE) protective clothing and equipment, as well as body armor and helmets, while performing their duties. The insulation and low permeability of the garments impedes heat loss and the added weight of armor and equipment increases the metabolic rate. The net result is increased heat strain. This study determined how well two developmental MCCS reduced heat strain under these conditions, despite the additional load carriage (i.e. weight of the MCCS). The study also compared the effectiveness of the modified Army Combat Shirt (ACS) relative to the standard Air Warrior micro-climate cooling garment (MCG).

After completing heat acclimation trials, eight male volunteers took part in 6 heat stress tests, with 6 clothing and equipment configurations all worn at Mission Oriented Protective Posture level 4 (MOPP 4). All tests were performed in a simulated extreme desert environment (51.7°C dry bulb (T_{db}), 16.6°C dew point (T_{dp}) (14% rh), 1.3 $m \cdot sec^{-1}$ wind speed). Each experimental trial consisted of three repeats of 35 minutes walking on a level treadmill at 3.2 $km \cdot h^{-1}$ (2.0 mph)

followed by 25 minutes of rest, for a total heat exposure of 180 min. Time weighted mean metabolic rate during the experiments was 269 watts. Each trial was a maximum of 3-hours, or until a given volunteer reached a core temperature of 39.5°C, or voluntarily withdrew.

In summary, both cooling systems reduced physiological heat strain measures relative to no cooling. Under the test conditions, neither cooling system provided sufficient cooling to allow for 11 hour flight missions while dressed at the MOPP 4 level. Testing the cooling systems at a more realistic temperature such as the 37.8°C (100°F) that was used in the flight simulator when the original Air Warrior system was developed, might better discriminate between the two systems and provide a clearer picture of how long Air Soldiers could work in the field.

INTRODUCTION

U.S. Soldiers may encounter chemical, biological, radiological, nuclear, and explosive (CBRNE) weapons during deployment. Intelligence sources estimate there are active chemical weapons programs in at least ten countries worldwide. Although there are multiple international conventions banning nuclear, biological and chemical warfare, several third world countries continue to develop, test, and evaluate nuclear weapons and chemical/biological warfare agents, and the means to disseminate them. The spread of these weapons increases the probability that Aircrew flying helicopter missions need to be protected against possible CBRNE weapons by wearing protective clothing.

Military operations during summer months in Afghanistan and portions of Southwest Asia are routinely conducted during daytime temperatures >32.2^{o} and >43.3^{o}C, respectively (15, 16). Temperatures inside helicopters being flown in these conditions can reach as high as 51.7°C. During flight operations, Aircrew may have to wear complete CBRNE protective clothing and equipment, as well as body armor and helmets, while performing their duties. The insulation and low permeability of the garments impedes heat loss and the added weight of armor and equipment increases the metabolic rate. The net result is increased heat strain. Previous research indicates that wearing CBRNE protective clothing during light and moderate work increases the effective wet bulb, globe temperature (WBGT) index by ~6°C and ~12°C respectively compared to wearing only the army combat uniform (ACU), (1,2,14). Wearing a combat helmet can increase air temperature around the head by 2-3ºC (3).

Environmental heat stress and physical activity adds more physiological heat strain than either one alone and may push physiological systems to their limits (8, 11, 12). One of the initial physiological responses to heat stress is increased skin blood flow. This allows conductive and convective heat transfer from the core to the skin, where heat can be lost to the environment through radiation and convection. To support this peripheral vasodilation, heart rate and cardiac output increase. During moderate exercise, the combined requirement of blood flow to the skin and the working muscles may cause cardiovascular strain and impair performance (10).

When ambient temperature is equal to or above skin temperature, evaporative heat loss from sweating accounts for almost all body cooling (12). The rate of sweat evaporation depends upon air movement and the water vapor pressure gradient between the skin and the environment. This gradient is impacted by the combination of clothing worn and equipment carried, both of which increase insulation and decrease vapor permeability. A micro-environment of higher temperature and vapor pressure, as well as minimal air movement is created next to the skin. The gradient for both dry and evaporative heat loss is reduced, and can lead to uncompensable heat stress, greater physiological heat strain, and performance decrements (6,11).

Clothing and equipment that can reduce the thermal load would delay cardiovascular strain and better sustain performance (10). The Air Warrior Program currently provides vapor compression, micro-climate cooling systems (MCCS) for their pilots as an effective way to reduce heat strain while flying missions in hot environments (5). Because the pilots are seated, the weight of the cooling system does not impose an additional metabolic burden on the user. However, the weight and bulk of the Air Warrior MCCS makes it untenable for use by crew members who perform their mission tasks while standing and moving around both on the ground and in the rear of the helicopter. The Air Warrior program has tried using a tethered multi-man MCCS in the rear of the helicopter, but it has proved awkward to perform mission duties while trailing tether lines to the multi-man cooler.

While the Air Warrior and multi-man MCCS have significant weight burden and/or logistic burdens, a lightweight, portable MCCS could potentially provide cooling to reduce thermal strain sufficiently to offset the increased metabolic cost of carrying the system. The Air Soldier System group of PM Air Warrior development document indicates a need to develop personally carried MCCS with sufficient cooling to “provide the capability to perform not less than 11 hours of flight operations (based on OMS//Mission Profiles) in MOPP 4 conditions” by the support crew. MOPP 4 is the CBRNE Mission Oriented Protective Posture level 4 which incorporates wearing a CB overgarment, overboots, gloves and mask. The requirement for cooling is mandated to be provided at 51.7°C at 14% relative humidity.

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PURPOSE

Objectives

- To compare the relative effectiveness of a 120 W (3.2 kg) MCCS and a 180 W (4.6 kg) MCCS used continuously for up to three hours for reducing heat strain in volunteers dressed in MOPP 4 and exercising in a 51.7°C Tdb, 14% rh environment.
- To compare these cooling systems using both the standard Air Warrior microclimate cooling garment (MCG) and a modified version of the Army Combat Shirt (ACS) with cooling tubes over the torso.

Hypotheses

- Continuous cooling provided by each MCCS is sufficient to reduce heat strain resulting in increased exercise time relative to no cooling even with the possible increased load carriage imposed by carrying the 120W (~3.2 kg) and 180W (~4.6 kg) mock-ups.
- Providing 180W of continuous cooling results in reduced heat strain and increased exercise time relative to providing 120W of continuous cooling, even with increased load carriage imposed by carrying the greater weight of the 180W mock-up.
- There is no difference in heat strain between wearing the Air Warrior MCG and the modified ACS when the same level of cooling is provided.

METHODS

EXPERIMENTAL DESIGN, PROCEDURES, AND MEASUREMENTS

Subjects

Eight male Soldiers were recruited to participate in this study. Before testing began all volunteers were fully briefed both orally and in writing on the purpose and risks of the study and gave their written consent to participate in the research. A medical officer cleared the volunteers for participation after a physical examination and medical history review.

Preliminary Tests

The volunteers' age, height, and weight were recorded. Percent body fat was estimated from skin folds taken at four sites (4). Metabolic rate was measured to calculate work – rest cycles for the experimental trials that would place the volunteers in the middle of the range of metabolic rates estimated for the different Air Soldier missions which are between 250 – 350 watts (13). By collecting metabolic data both while the volunteers walked on a treadmill and then recovered during seated rest, it was determined that setting the treadmill at 2.0 mph, 0% grade and using cycles of 35 minutes of walking and 25 minutes of seated rest would place the volunteers within this range. Metabolic rate was determined from a 90 second sample of expired air collected after ~10 min of exercise and after ~10 minutes of seated rest using indirect calorimetry via Douglas Bags, dry gas meter, and TrueMax© metabolic cart. Collecting metabolic rates during the experiments was unfeasible because the volunteers were dressed in MOPP 4 wearing the chemical protective face mask.

Volunteers completed a heat acclimation program prior to experimental testing to standardize their physiological state and to reduce the risk of exhaustion from heat strain during the experimental trials. Heat acclimation consisted of 10 days of exercise in a 51.7°C (125°F), 14% rh (34.5°C (94.1°F) WBGT) environment while wearing the Army Improved Physical Fitness Uniform for the first six days and the Army Combat Uniform (ACU) for the final four days. Rectal core temperature and heart rate were measured throughout all heat stress exposures. Starting on day 7 of heat acclimation, skin temperatures were collected using thermistors taped to five positions (chest, back, forearm, thigh, and calf). Because the volunteers would wear a chemical protective mask during exercise-heat trials they were familiarized with wearing them during the heat acclimation. Starting on day two, they wore the mask for 20 minutes, and increased wear time by 20 minutes per day until they reached a max wear time of 60 minutes. Treadmill speed was set at 3.5 mph and 4% grade. Volunteers walked continuously until one of three criteria were met: 1) 100 minute walk completed; 2) rectal temperature reached 39.5°C (103.1°F); or 3) volitional exhaustion. To limit dehydration, volunteers drank 250 ml of water prior to beginning each heat acclimation session, and receive 450 ml of water every 20 minutes during heat acclimation. Pre- and post-exercise weights were recorded daily. Each day at the end of heat acclimation, the volunteers drank sufficient liquid to return within 1% of their first morning weight to assure that they did not undergo a progressive dehydration.

Cooling Tests

Design. There were 6 heat stress tests, with 6 clothing and equipment configurations worn as shown in Table 1. All tests were performed in a simulated extreme desert environment (51.7°C dry bulb (T_{db}), 16.6°C dew point (T_{dp}) (14% rh), 1.3 $m \cdot sec^{-1}$ wind speed).

Each experimental trial consisted of three repeats of 35 minutes walking on a level treadmill at 3.2 $km \cdot h^{-1}$ (2.0 mph) followed by 25 minutes of rest, for a total heat exposure of 180 min. Time weighted mean metabolic rate during the experiments was 269 watts. Each trial was a maximum of 3-hours, or until a given volunteer reached a core temperature of 39.5°C, or voluntarily withdrew.

Clothing and Equipment. Each day, volunteers wore the same Air Warrior MOPP 4 clothing and equipment provided from the list shown in Appendix A, weighing approximately 27 kg depending on helmet and armor size. Two of these trials evaluated the fielded Air Warrior MCG, and two evaluated an ACS modified with liquid cooling tubes at two levels of cooling (120W and 180W). Two non-cooling trials were also conducted; one with volunteers wearing a flame resistant t-shirt instead of the MCG and one with volunteers wearing the modified ACS with no cooling provided. Garments were laundered daily.

In the cooling trials, the volunteers carried the appropriate sized mock-up of the cooling unit. Mock-ups were used to represent the size and weight of each prototype cooling system while cooling was provided by a large commercial water chiller and pumps. This allowed measurement of water temperature flowing into and out from the two cooling garments used in the study so that cooling power could be calculated. Flow rate and water temperature provided by the systems was based on the results of copper manikin testing that estimated these requirements for the torso surface area covered by the microclimate cooling garments. Cooling was provided continuously during these trials.

Table 1. Matrix for 6 trial configurations

CON – No cooling. Exercise while wearing Air Warrior MOPP 4 over a fire resistant t-shirt	MCG LO - Exercise while wearing Air Warrior MOPP 4 plus Air Warrior MCG and a mock-up of 120W cooling system.	MCG HI - Exercise while wearing Air Warrior MOPP 4 plus Air Warrior MCG and a mock-up of 180W cooling system.
ACS – No cooling. Exercise while wearing Air Warrior MOPP 4 over the modified ACS	ACS LO – Exercise while wearing Air Warrior MOPP 4 plus modified ACS and a mock-up of 120W cooling system.	ACS HI – Exercise while wearing Air Warrior MOPP 4 plus modified ACS and a mock-up of 180W cooling system.

Statistical Analysis

Primary comparisons were made among the combination of CON, MCG LO, and MCG HI as the current proposed uniform and ACS, ACS LO, and ACS HI, which would be a potential next generation uniform configuration. Analyses were completed on total exposure time, watts of cooling, equipment weight, sweat rate, changes in skin temperature, core temperature and heart rate during the first walk, and calculated time to reach 39.5°C in each clothing configuration. A one-way (trial) analysis of variance for repeated measures was performed on each variable. A significant *F*-test was further analyzed with Student-Newman-Keuls *post hoc* test to detect differences among means. Sample size estimates were made *a priori* using α=0.05 and β=0.20 values and assuming a standard deviation of 0.3°C for T_c (1). Power analysis revealed that 5 subjects were sufficient to detect a 1.25-fold (0.375°C) difference for T_c between groups. Statistical significance was set at $p<0.05$. All data are presented as mean ± SD.

RESULTS

The age, height, weight, body fat, and body surface area of the volunteers were: 22.6 ± 3.2 years, 177 ± 6 cm, 82.6 ± 10.1 kg, 16.3 ± 2.4%, and 2.0 ± 0.1 m^2 respectively.

Weight of equipment worn and carried for each cooling condition was significantly different ($p < 0.01$) among all configurations in both environments. MCG HI (31.8±1.4 kg) was greater than MCG LO (30.4±1.1 kg) which was greater than CON (26.1±0.9kg). ACS HI (32.0±1.4 kg) was greater than ACS LO (30.7±1.6 kg), which was greater than ACS (26.9±1.4 kg). Note that the ACS cooling shirt, which is long sleeved and contains water filled tubing, weighed more than the fire resistant t-shirt used for CON.

Mean weighted metabolic rate during exercise was 376±57 watts and during recovery was 119±28 watts. With subjects performing repeated cycles of 35 minutes of walking and 25 minutes of seated recovery, the calculated metabolic rate for combined exercise and rest was 269 watts.

There were significant differences among the mean cooling rates in both sets of configurations. The mean cooling provided during MCG HI (201±41 W) was significantly greater ($p<0.05$) than cooling during MCG LO (160±10 W) trials and the mean cooling provided during ACS HI (215±20 W) was significantly greater than cooling during ACS LO (150±31 W) ($p<0.05$) (Figure 1). There were no differences between configurations at the same cooling rate.

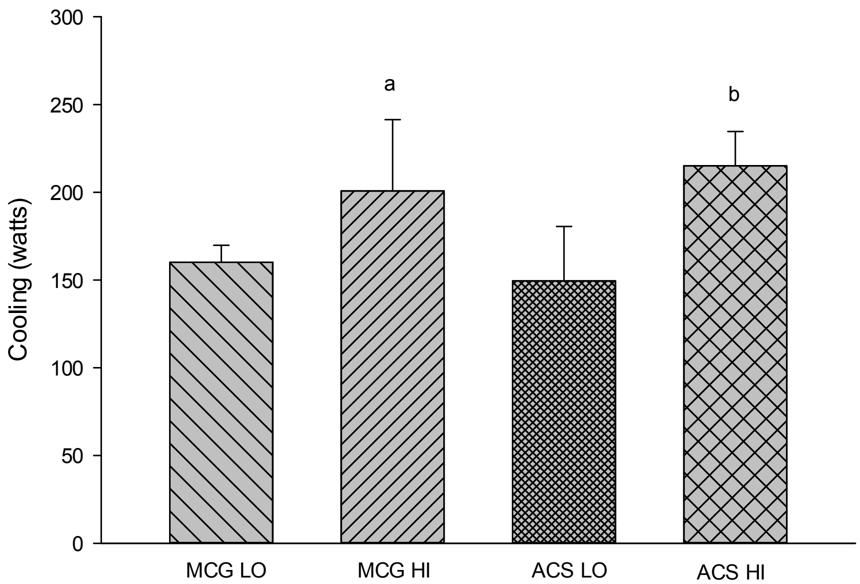

Figure 1. Watts of cooling provided in each configuration during experiments at 51.7°C, 14% rh. a) MCG HI significantly different from MCG LO ($p<0.05$). b) ACS HI significantly different from ACS LO ($p<0.05$)

No volunteers completed the 180 minute experiments without cooling. Two volunteers completed the total time in MCG LO and one volunteer finished in ACS LO. Four volunteers completed the total time in MCG HI and five volunteers finished in ACS HI. Total experimental time in MCG HI (134.8±49.7 min) and MCG LO (123.8±43.0 min) were both significantly greater ($p<0.05$) than in CON (72.8±11.7 min) (Figure 2). Total experimental time in ACS HI (145.4±51.3 min) and ACS LO (113.8±35.0 min) were both significantly greater ($p<0.05$) than ACS (57.6±15.2 min) (Figure 2). There were no significant differences between either MCG HI and MCG LO or ACS HI and ACS LO. Also, there were no significant differences in exposure time with matching cooling rates between the MCG and ACS configurations.

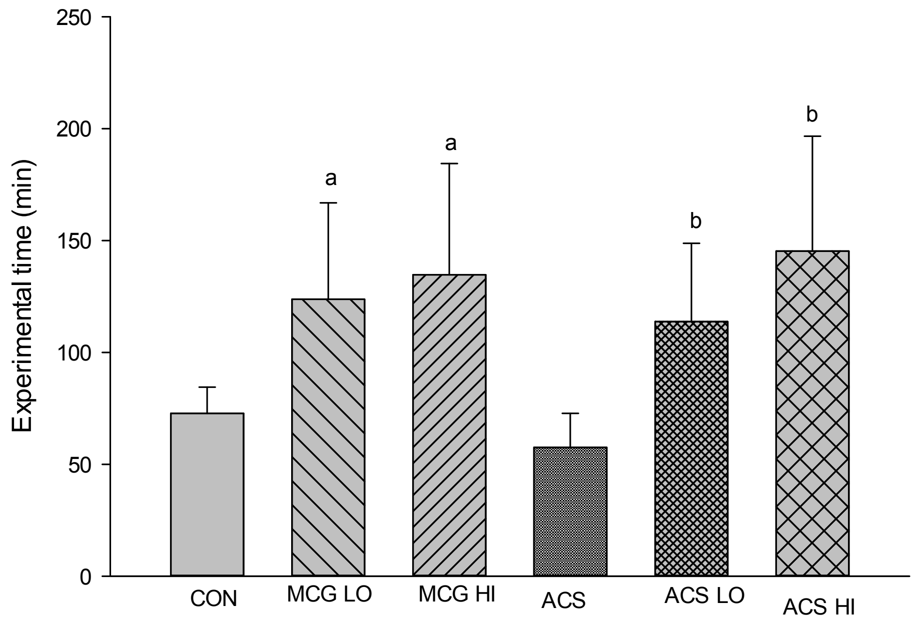

Figure 2. Time to voluntary exhaustion in each experimental configuration at 51.7°C, 14% rh. a) MCG Hi and MCG LO significantly different from CON ($p<0.05$). b) ACS HI and ACS LO significantly different from ACS ($p<0.05$).

The combination of the extreme environmental temperature and the development of neck and shoulder discomfort while walking wearing the redesigned Air Warrior program body armor resulted in volunteers dropping out early, even when receiving high levels of cooling. Therefore, the three primary indicators of heat strain were calculated for the first 35 minute exercise period that was completed by all subjects. These included change in skin temperature, change in heart rate and change in core temperature. Increases in skin temperature with MCG HI (0.87±0.64°C) and MCG LO (1.18±0.89°C) were not significantly different from each other but were both significantly less than the increase with CON (2.46±0.34°C). Similarly, the increases in skin temperature with ACS HI (0.87±0.76°C) and ACS LO (1.28±0.73°C) while not significantly different from each other were significantly less than with ACS alone (2.63±0.36°C) (Figure 3).

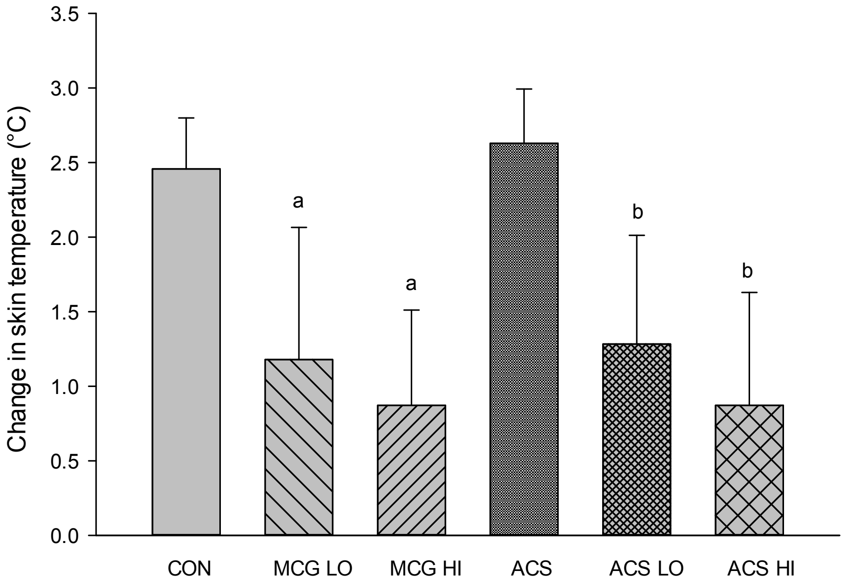

Figure 3. Change in skin temperature over the first 35 minutes of exercise in all configurations at 51.7°C, 14% rh. a) MCG HI and MCG LO significantly different from CON ($p<0.05$). b) ACS HI and ACS LO significantly different from ACS ($p<0.05$).

The increases in HR with MCG HI (40±11 b·min^{-1}) and MCG LO (44±7 b·min^{-1}) were not significantly different from each other, but were both significantly less than with CON (55±11 b·min^{-1}). Similarly, the increases HR with ACS HI (40±7 b·min^{-1}) and ACS LO (42±10 b·min^{-1}) were not significantly different from each other, but were both significantly less than with ACS alone (54±11 b·min^{-1}) (Figure 4). The increases in core temperature with MCG HI (0.42±0.20°C) and MCG LO (0.42±0.16°C) were both significantly less than with CON (0.60±0.09°C). The increases in core temperature with ACS HI (0.48±0.21°C) with ACS LO (0.49±0.17°C) and with ACS (0.52±0.13°C) were not significantly different from each other (Figure 5).

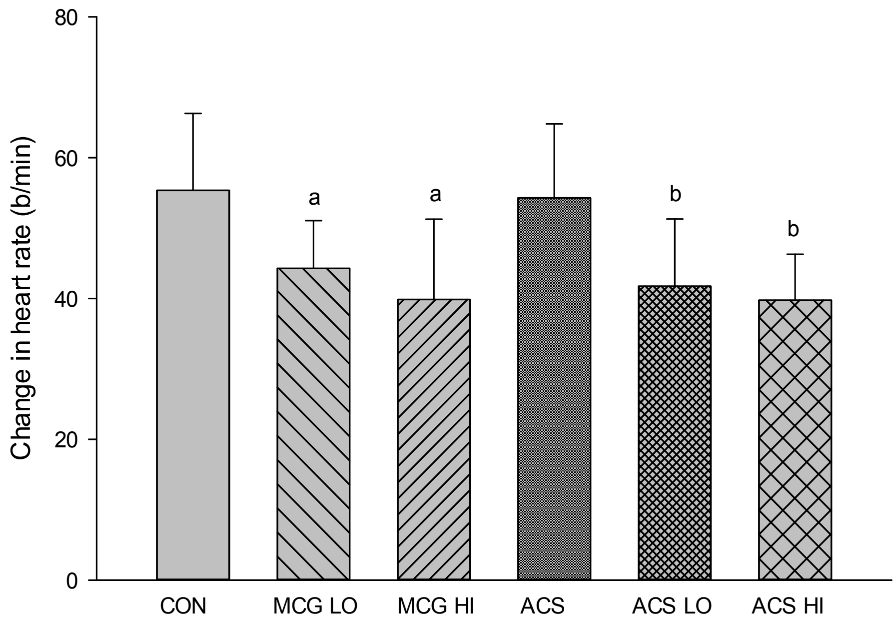

Figure 4. Change in heart rate over the first 35 minutes of exercise in all configurations at 51.7°C, 14% rh. a) MCG HI and MCG LO significantly different from CON ($p<0.05$).
b) ACS HI and ACS LO significantly different from ACS ($p<0.05$).

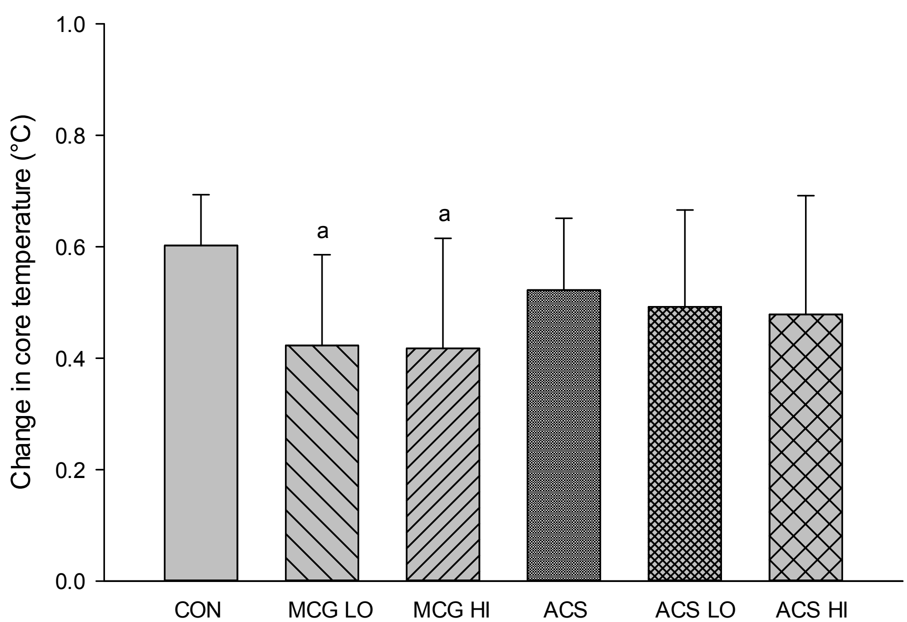

Figure 5. Change in core temperature over the first 35 minutes of exercise in all configurations at 51.7°C, 14% rh. a) MCG HI and MCG LO significantly different from CON ($p<0.05$).

Limiting factors to work time in the heat are multi-faceted, impacted by skin temperature, core temperature, heart rate, hydration and comfort level among other factors. However, one simple component to look at to approximate endurance time when exercising in MOPP 4 is the T_{re} to T_{sk} gradient (10). A study by Sawka et al. (9) analyzing aggregate data from 747 laboratory trials and 131 field trials noted that 50% of subjects incurred exhaustion from the heat by a core temperature of 38.5°C in the laboratory trials and a core temperature of 39.5°C in the field trials when exercising in uncompensable heat stress conditions with high skin temperatures. Therefore, the rate of change in T_c during each minute was determined for each subject in each test condition and used to predict time to reach a T_c of 39.5°C from a baseline core temperature of 37°C. Of the eight subjects analyzed, one individual was a significant outlier, with a calculated time to reach 39.5°C being three to seven times greater than the rest of the subjects in the MCG HI trial. This subject showed large core temperature drops of 0.39 and 0.49°C during the second and third rest periods, while the other three subjects who made it that through the second rest period exhibited core temperature drops of less than 0.1°C during each rest period. While these large temperature drops by the one subject were likely actual physiological responses to the cooling and not the result of equipment malfunction, they are so far from the norm displayed by the other subjects that calculated times to 39.5°C for the test group are presented both with and without the presence of this subject's data. This will allow the developers to evaluate for themselves the impact of this one individual's response relative to the effectiveness of the cooling systems. Therefore, the following paragraph first presents data on the calculated time to reach 39.5°C using seven volunteers, followed by the calculated time to reach 39.5°C using all eight volunteers.

Based on the rates of core temperature change in seven subjects, the calculated time to reach 39.5°C in the MCG HI trial (292±131 min) was no different than in the MCG LO trial (226±38 min), but both were significantly longer than in CON, which was 120±6 min. The calculated time to ACS HI (290±73 min) was significantly greater than both ACS LO (193±52 min) and ACS (140±45 min), which were not different from each other (Figure 6A). Using all eight subjects, the calculated time to reach 39.5°C in the MCG HI trial was 451±465 min, which was significantly ($p<0.05$) greater than in CON (123±14 min), but not different from MCG LO (226±38 min). Using the data from all eight subjects there were no significant differences among ACS HI (346±171 min), ACS LO (202±55 min) and ACS (141±42 min) in calculated time to 39.5°C (Figure 6B).

Sweating rates with both MCG HI (16.7±4.0 $g{\cdot}min^{-1}$) and with MCG LO (20.7±6.1 $g{\cdot}min^{-1}$) were significantly less than with CON (28.1±4.3 $g{\cdot}min^{-1}$). Sweating rates with both ACS HI (18.0±5.0 $g{\cdot}min^{-1}$) and with ACS LO (21.5±5.3 $g{\cdot}min^{-1}$) were significantly less than with ACS (35.6±11.7 $g{\cdot}min^{-1}$). While there were no differences between MCG HI and ACS HI or MCG LO and ACS LO, sweating rate with CON was significantly less than with ACS (Figure 7). However, this difference was not physiologically significant enough to impact calculated time to reach a core temperature of 39.5°C.

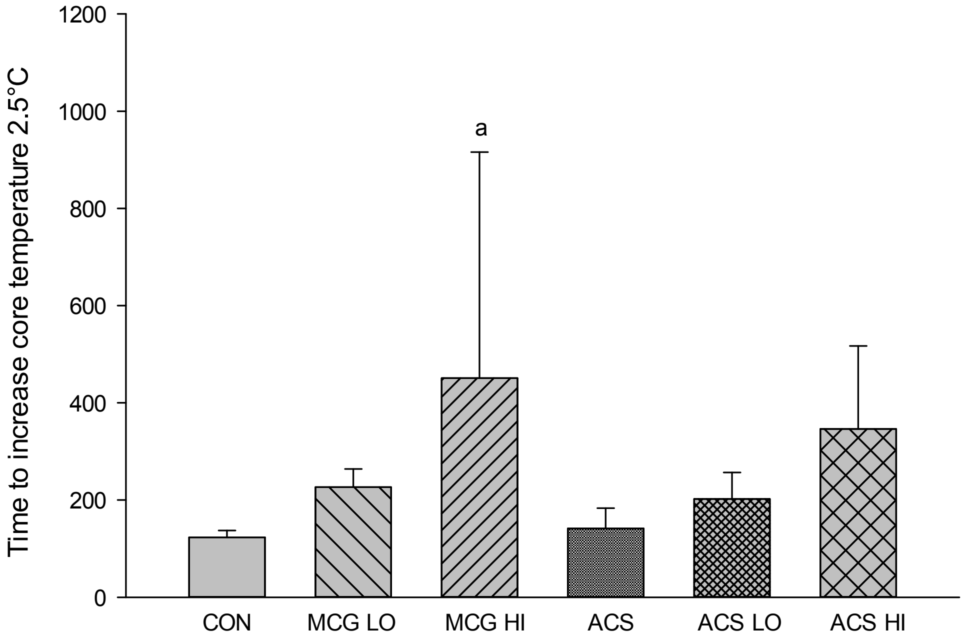

Figure 6A. Calculated time for core temperature (n=8) to increase 2.5°C (to 39.5°C) based on core temperature changes during experiments in all configurations at 51.7°C, 14% rh. a) MCG HI significantly different from CON ($p<0.05$).

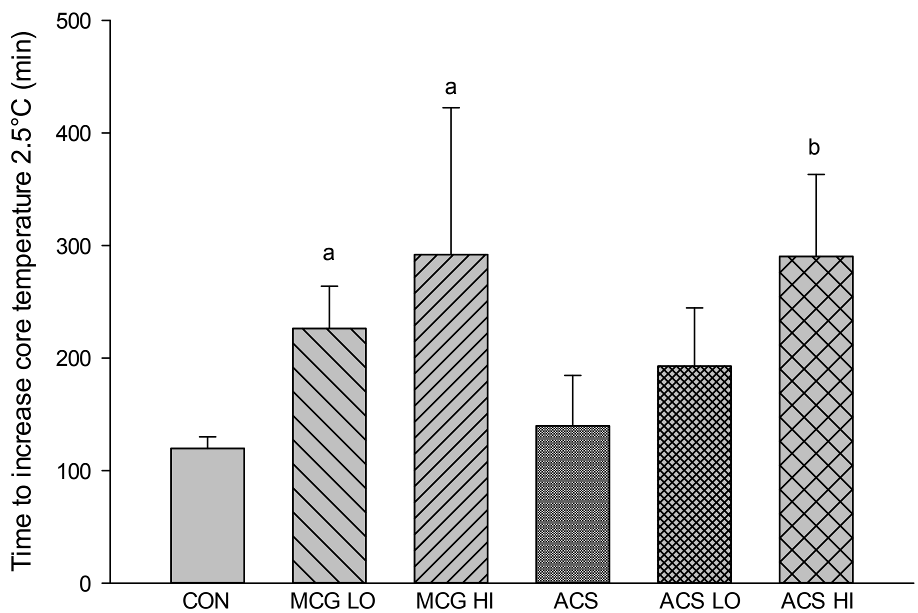

Figure 6B. Calculated time for core temperature (n=7) to increase 2.5°C (to 39.5°C) based on core temperature changes during experiments in all configurations at 51.7°C, 14% rh. a) MCG HI and MCG LO significantly different from CON ($p<0.05$). b) ACS HI significantly different from ACS LO and ACS ($p<0.05$)

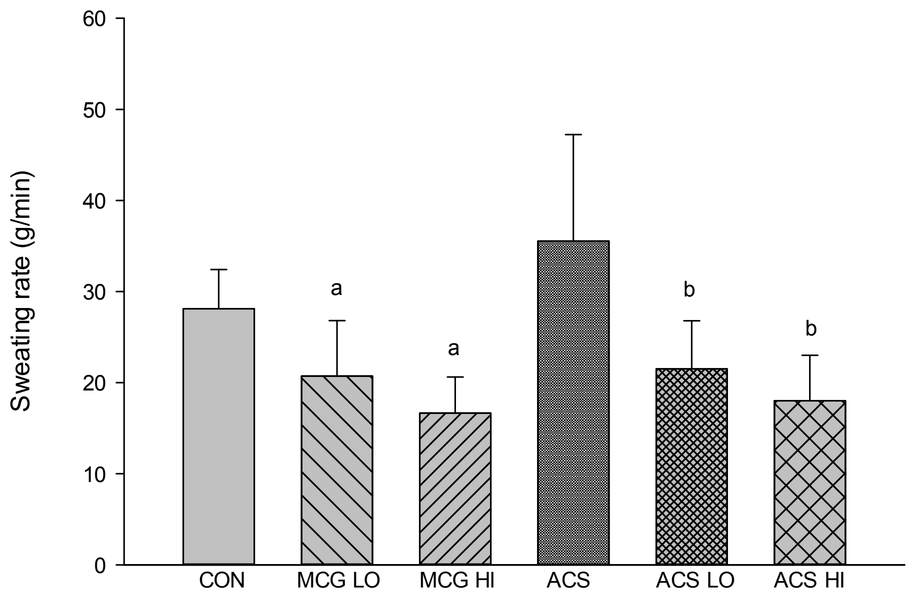

Figure 7. Sweating rate during experiments in all configurations at 51.7°C, 14% rh. a) MCG HI and MCG LO significantly different from CON ($p<0.05$). b) ACS HI and ACS LO significantly different from ACS ($p<0.05$).

SUMMARY

The purpose of this project was to compare the relative effectiveness of 120W and 180W cooling systems to reduce physiological heat strain in volunteers completing up to three hours of exercise-heat stress. As expected, more volunteers were able to complete testing when receiving HI cooling, compared to LO, with no volunteers completing the trials with no cooling. Predicted endurance time, based on rate of change in Tc as impacted by the T_c-T_{sk} gradient, was more than doubled by HI, compared to no cooling, with LO producing about half as great an increase in exposure duration.

The mandate from the Air Warrior program was the use of a lightweight, portable microclimate cooling system to "provide the capability to perform not less than 11 hours of flight operations (based on OMS//Mission Profiles) in MOPP 4 conditions" by the support crew. This requirement for cooling is to be provided at 51.7°C at 14% relative humidity. While it is reasonable to mandate that the cooling systems be able to operate at 51.7°C for 11 hours, this is not a realistic operational scenario. The average daily temperature range for July in Baghdad ranges from 25°C (77°F) to 44°C (111°F) and for August in Kandahar ranges from 23°C (73°F) to 40°C (104°F). Additionally, as the sun arcs across the sky during an 11 hour work day, temperature inside the helicopter will be affected by varying radiant loads both from direct sunlight and from the ground. Therefore, it is unlikely that the Air Soldier will be working in a 51.7°C degree environment for an extensive portion of the day, and that the external heat stress will be less than this for a majority of the day, reducing the strain on the cooling system. While both the HI and LO systems showed significant reduction in heat strain measurements of T_{sk}, T_c, HR, and SR relative to CON and ACS experiments, the combination of the external impact of the high ambient temperature coupled with the metabolic heat produced from exercise resulted in a significant rate of heat storage that limited the impact of either cooling system.

Additionally, in order to create realistic average energy expenditures for the volunteers that were representative of energy expenditures of actual Air Soldier tasks, we created a repetitive walk – rest scenario. While this scenario created metabolic rates equivalent to those of typical Air Soldier tasks, it was not necessarily representative of the amount of time actual Air Soldiers would spend on their feet continuously while performing their duty assignments. Therefore, the design of the exercise task may have led in part to the shoulder and back pain that would not necessarily happen in some Air Soldier missions because they might not have to be on their feet for 35 consecutive minutes.

Limitations

The total exposure time for a given experiment was impacted by discomfort from modifications to the body armor as part of the Air Warrior Program. As part of a weight reduction effort within the program, the shoulder straps of the body armor were narrowed relative to those on the standard IOTV. Because the volunteers in this project had to walk for 35 minutes of every hour, the weight of the body armor pulling down across the narrower straps eventually resulted in back pain almost universally with the volunteers, with pain across the upper back being the most common complaint for stopping exercise on any given day. Subjects stopped work early as a result of sore shoulders or sore backs in 14 of the 48 individual test exposures. This was regardless of the cooling provided by the systems to the volunteer. Even with the back discomfort experienced by the volunteers, their exposure times with both HI and LO cooling in both the MCG and ACS configurations were greater than experiments with no cooling in either configuration. Unfortunately, even though data showed reduction in heat strain from the effect of both HI and LO cooling over the first 35 minutes, the benefit of the cooling system to remove stored heat during rest was not able to be fully evaluated due to so many volunteers withdrawing early.

In summary, both cooling systems reduced physiological heat strain measures relative to no cooling. Under the test conditions, neither cooling system provided sufficient cooling to allow for 11 hour flight missions while dressed at the MOPP 4 level. Testing the cooling systems at a more realistic temperature such as the 37.8°C (100°F) that was used in the flight simulator at USAMRL when the original Air Warrior system was developed might better discriminate between the two systems and provide a clearer picture of how long Air Soldiers could work in the field.

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APPENDIX A: Air Soldier CBRNE Clothing and Equipment

Flyers' glove GS/FRP-2, MIL-G
Combat Knife: ASEK, Sheath and Leg Straps
Universal Holster Assembly (thigh-mounted)
9mm weapon with loaded magazine
4-M9 Ammunition magazines
4-M4 Ammunition magazines
Army Combat Boots (Hot Weather FR)
Vest, Survival
Signaling Platform
Flare Kit A/P 25S-5A
Mirror, Emergency Signal PN WG0601
Compass, Magnetic
Light, Marker, Distress FRS/MS-2000M (Firefly II
Whistle
First Aid Platform w/ contents
Tourniquet Pocket
Carabiner Non-Locking (qty 2)
Extraction Strap
Safety Restraint Tether (SRT)
Multi-Purpose Pouch (MPP) (qty 2)
Flashlight (Phantom Warrior 4AA version)
Combat Application Tourniquet (CAT)
Utility Pouch
Magazine Pouch, M-4 (qty 2)
Radio Pouch
Extension Tether (w/ Locking Carabiner)
Retaining Loop Abrasion Cover
Flexible Body Armor
ESAPI
Underlayer 1 Top

Underlayer 1 Bottom
Socks, wool, cushion sole, standard issue
Microclimate cooling garment (MCG)
M-45 protective mask
M-45 Blower and Filter
Blower Pouch
JPACE
Liquid chemical protective glove, 7 mil butyl rubber
Black Vinyl Overboot (BVO)
M291 Decontamination Kit
M295 Decontamination Kit
Atropine Injectors
Decontamination Papers
Flyers Helmet w/ANVIS Mount
Boom Mic Connecting Lip Light
Lip Light battery pouch w/ 2 AA batteries
AN/AVS-6 Image Intensifier Night Vision
AN/AVS-7 Heads-Up Display (HUD Monacle and cable)
NVG Battery Assembly w/ 4 AA batteries
Maxillo-Facial Shield
Communications Ear Plug (CEP) w/24" Extension Cable (PN CEP199-X02), Interface Harness (PN CEP900-I04, and One Pair of Foam Tips from PN CEP300 EMXP.
Laser Eye Protection Visor (Brown)
Laser Eye Protection Visor (Green)
AN/PRQ-7 CSAR Handheld Radio (HHR) PN: 4866112-101, Combat Survivor Evader/Locator (CSEL)
BB-2001A/U AN/PRQ-7 Rechargeable Battery Pack PN: BT-70581A
AWIS
AWIS Pocket (EME)
AWIS w/ 3 batt
Wireless Encryption Device (WED)